LAPP-EXP 99.04

BOSE-EINSTEIN CORRELATIONS AND COLOR RECONNECTION EFFECT IN W PAIR DECAY AT LEP2.

F. MARTIN
Laboratoire de Physique des Particules (LAPP), IN2P3-CNRS,
F-74019 Annecy-Le-Vieux Cedex, France

The analyses of the Bose-Einstein correlations and color reconnection effect performed by the four LEP collaborations in W pairs produced in e^+e^- annihilations at LEP2 are presented. To what extent these two effects could occur between the decay products of the two W in the $W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$ channel is still controversial. Such interconnection effects, if they exist, may influence the W mass measured by direct reconstruction of the decaying W at center of mass energies of 172, 183 and 189 GeV. The opposite conclusions obtained by ALEPH and DELPHI concerning Bose-Einstein correlations between pions coming from different W are presented. New results of L3 using LEP 1 data are discussed. Possible indication by the DELPHI collaboration of color reconnection is also mentioned.

1 Introduction

The existence of Bose-Einstein correlations between identical bosons in interactions producing hadronic final states is well established [1,2,3,4]. This effect leads to an enhancement of the two particle differential cross section for pairs of identical pions close in phase space. First observations of these correlations in the W pair production at LEP2 have already been reported [5,6]. The first part of this contribution is devoted to the analysis of this effect in W pair production by the LEP collaborations.
Color reconnection could be important in the non-perturbative phase of the fragmentation [7] but there is no exact calculation of the size of this effect in non-perturbative QCD. A possible signature of color reconnection effect between W decay products could be observed as a reduction of the charged multiplicity of $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ events compared to twice those of $W^+W^- \rightarrow q_1\bar{q}_2l\nu_l$ events. The second part of this contribution reports the measurements of the charged multiplicity in W pair events.

2 Bose-Einstein Correlations

2.1 ALEPH analysis

The ALEPH experiment has analysed the data recorded at center of mass energies of 172, 183 and 189 GeV [10]. The Bose-Einstein correlations (BEC) occur for the like sign pion pairs at low values of Q, where $Q^2 = (\mathbf{p_1} - \mathbf{p_2})^2 - (E_1 - E_2)^2$ is Lorentz invariant. To see any enhancement of the two particle cross section for pairs of identical pions, a sample identical to the like charged pion pair sample, except for the presence of BEC, is needed. ALEPH has chosen the unlike-sign pion pairs as reference sample. But, other sources of correlations (mainly resonances) can bias this reference sample. Therefore, the ratio $R(Q) = N^{\pm\pm}(Q)/N^{+-}(Q)$ for the data, where $N^{\pm\pm}(Q)$ is the number of like-sign pion pairs and $N^{+-}(Q)$ the number of unlike-sign pion pairs, has been normalized to the same ratio, obtained with the Monte-Carlo events without BEC:

$$R^*(Q) = \left(\frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}\right)^{data} / \left(\frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}\right)^{MC\ no\ BE} . \tag{1}$$

ALEPH has parametrized the observed effect with:

$$R^*(Q) = \kappa(1 + \epsilon Q)(1 + \lambda \exp^{-\sigma^2 Q^2}), \tag{2}$$

where κ is a normalization factor and the term $(1 + \epsilon Q)$ takes into account some long range correlations, due to charge or energy-momentum conservation. The $(1 + \lambda \exp^{-\sigma^2 Q^2})$ term parametrizes the Bose-Einstein effect, λ being the magnitude of the effect and σ the mean size of the regions which emit pions with similar energy and momentum [a].
A model (JETSET BE_3 [8]) of BEC has been adjusted by ALEPH on the data recorded at 91 GeV at the Z peak. The parameters of this model have been adjusted to $\lambda = 2.3$ for the magnitude of the effect and $R = 1/\sigma$=0.26 GeV for the source size. A b-tagging algorithm [9] has been used to select $Z \rightarrow b\bar{b}$ events, allowing to measure BEC in b flavor and in u, d, s, c flavors at the Z peak separately. Residual discrepancies between data and Monte-Carlo for u, d, s, c flavors have been corrected bin by bin. The prediction of this model tuned and corrected at the Z peak is in good agreement with the data in the $W^+W^- \rightarrow q_1\bar{q}_2l\nu_l$ events.

In the $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ channel, two cases have been considered, depending on whether BEC are allowed between pions coming from different W (FC for *full correlations* in what follows)

[a] These definitions will be kept throughout this contribution.

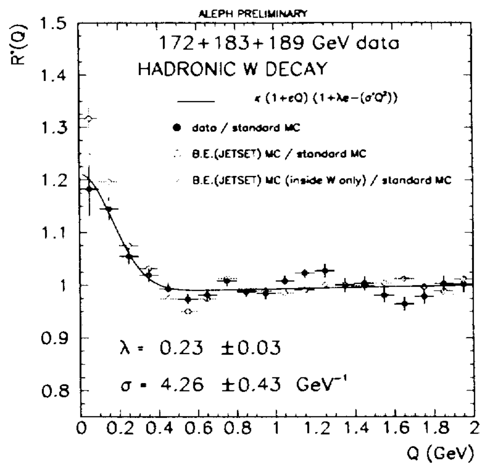

Figure 1: Comparison of the $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ data with the JETSET model predictions for two different hypothesis, depending on whether pions coming from different W are correlated or not. The result of the fit to the data is also shown.

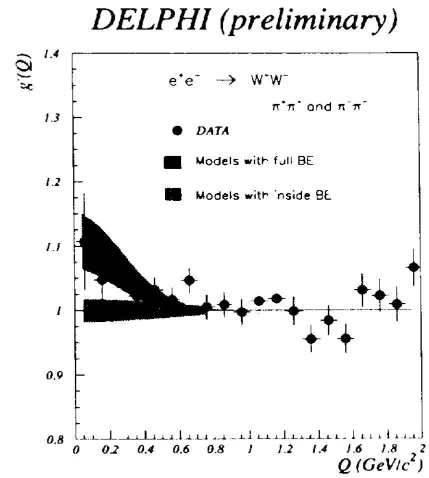

Figure 2: Comparison of the $g'(Q)$ distribution for the fully hadronic WW data with the $g'(Q)$ distribution for the original JETSET Monte-Carlo model in two different cases, depending on whether or not BEC exist between pions coming from different W.

or not (NFC). Figure 1 shows the comparison of the data to these different models and the result of the fit to the data. A second fit to the four first bins, where the effect is maximum, has been performed, where all parameters but λ have been fixed. The differences between the data and the two models are

$$\lambda^{data} - \lambda^{MC\ FC} = -0.088 \pm 0.026\ (stat) \pm 0.020\ (syst) \tag{3}$$

$$\lambda^{data} - \lambda^{MC\ NFC} = -0.019 \pm 0.026\ (stat) \pm 0.016\ (syst). \tag{4}$$

These results disfavoured the hypothesis of correlations between pions from different W at 2.7 standard deviations.

2.2 DELPHI analysis

The DELPHI experiment has analysed the data recorded at center of mass energies of 172 [5], 183 and 189 GeV [11]. In order to compute the correlation function $R(Q) = N^{\pm\pm\ data}(Q)/N_0^{\pm\pm}(Q)$, DELPHI has calculated the reference distribution $N_0^{\pm\pm}(Q)$ using events generated by PYTHIA [12] without BEC. DELPHI has parametrized the effect with:

$$R(Q) = 1 + \lambda \exp^{-\sigma^2 Q^2}. \tag{5}$$

The bin-to-bin correlations have been evaluated and taken into account. This increases the statistical error by about 25% in $W^+W^- \rightarrow q_1\bar{q}_2 l\nu_l$ channel (2q), and by 50% in the $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ (4q) channel. The final values of the parameters are: $\lambda = 0.399 \pm 0.060\ (stat) \pm 0.026\ (syst)$, $\sigma = 0.622 \pm 0.061\ (stat) \pm 0.022\ (syst)$ fm and $\lambda = 0.365 \pm 0.036\ (stat) \pm 0.047\ (syst)$, $\sigma = 0.622 \pm 0.042\ (stat) \pm 0.031\ (syst)$ fm for the semi-leptonic events and the fully hadronic events respectively. In order to perform a direct measurement sensitive to BEC between particles from different W, DELPHI has defined the ratio

$$g(Q) = \frac{N_{4q}^{\pm\pm}(Q)}{N_{mix}^{\pm\pm}(Q)}, \tag{6}$$

where $N_{4q}^{\pm\pm}(Q)$ is the distribution of like-sign pion pairs of (4q) events, and $N_{mix}^{\pm\pm}(Q)$ is the distribution of like-sign pion pairs of (4q)-like events, obtained by mixing two (2q) events. The double ratio

$$g'(Q) = \frac{g(Q)^{data}}{g(Q)^{MC\ no\ BE}}, \tag{7}$$

where $g(Q)^{MC\ no\ BE}$ has been obtained with a Monte-Carlo simulation without BEC, has been used to correct any possible distortions introduced by the event mixing method. This double ratio has been fitted to a Gaussian:

$$g'(Q) = 1 + \Lambda \exp^{-k^2Q^2}, \tag{8}$$

where Λ represents the fractional excess of number of pairs in fully hadronic channel at Q=0. The distribution of $g'(Q)$ for data is shown on figure 2, and compared to Monte-Carlo predictions in two different cases, depending on whether or not BEC exist between pions coming from different W. The fitted value of the parameter Λ is

$$\Lambda = 0.073 \pm 0.025\ (stat) \pm 0.018\ (syst), \tag{9}$$

and favours the hypothesis of correlations between pions coming from different W at 2.4 standard deviations.

2.3 OPAL analysis

The OPAL experiment has analysed the data recorded at center of mass energies of 172 and 183 GeV [6]. Three event samples have been studied: $W^+W^- \to q_1\bar{q}_2 l\nu_l$, $W^+W^- \to q_1\bar{q}_2 q_3\bar{q}_4$ or $(Z^0,\gamma)^* \to q\bar{q}$. For each sample, the correlation function is $R(Q) = N^{\pm\pm}(Q)/N^{+-}(Q)$, and is parametrized with

$$R(Q) = \kappa(1 + \epsilon Q + \delta Q^2)(1 + f_\pi(Q)\lambda \exp^{-\sigma^2 Q^2}), \tag{10}$$

where $f_\pi(Q)$ is the probability that a selected track pair is really a pair of pions. The $(1 + \epsilon Q + \delta Q^2)$ term takes into account the behaviour of the correlation function at high Q values due to long-range particle correlations. The contribution of the background has been taken into account by defining the correlation function as:

$$R(Q) = \frac{N_{sameW}^{\pm\pm}(Q) + N_{diffW}^{\pm\pm}(Q) + N_{Z^*}^{\pm\pm}(Q)}{N_{sameW}^{+-}(Q) + N_{diffW}^{+-}(Q) + N_{Z^*}^{+-}(Q)}, \tag{11}$$

where $N_{sameW}^{\pm\pm(+-)}(Q)$, $N_{diffW}^{\pm\pm(--)}(Q)$ and $N_{Z^*}^{\pm\pm(+-)}(Q)$ are the number of (un)like-sign track pairs for the class of pions from the same W boson, from different W bosons and from $(Z^0,\gamma)^* \to q\bar{q}$ events. Eq. 11 can be rewritten as

$$R^{had}(Q) = P_{same}^{had}(Q)C_{same}(Q) + P_{Z^*}^{had}C_{Z^*}^{had}(Q) + (1 - P_{same}^{had}(Q) - P_{Z^*}^{had})C_{diff}(Q), \tag{12}$$

where $C_{same}(Q)$, $C_{diff}(Q)$ and $C_{Z^*}(Q)$ are the BEC for the class of pions from the same W boson, different W boson and from $(Z^0,\gamma)^* \to q\bar{q}$ events, and the probabilities $P_{same}^{had}(Q)$ and $P_{Z^*}^{had}(Q)$ are taken from Monte-Carlo simulations without BEC. In the same way, the correlation function for the semi-leptonic event sample and those for $(Z^0,\gamma)^* \to q\bar{q}$ event sample can be written as a sum of different contributions. A simultaneous fit to these distributions has been done, assuming a common source size for all event classes. The following results have been obtained, using 183 GeV data only:

$$\lambda_{same} = 0.63 \pm 0.19\ (stat) \pm 0.14\ (syst), \quad \lambda_{diff} = 0.22 \pm 0.53\ (stat) \pm 0.14\ (syst) \tag{13}$$

$$\lambda_{Z^*} = 0.47 \pm 0.11\ (stat) \pm 0.08\ (syst), \quad \sigma = 0.92 \pm 0.09\ (stat) \pm 0.09\ (syst)\ fm. \tag{14}$$

It was not possible to establish, at this level of statistical precision, whether BEC between pions from different W bosons exist or not.

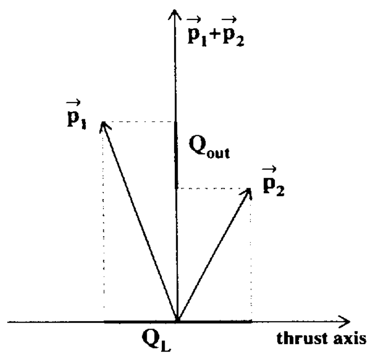

Figure 3: The longitudinal center of mass frame (LCMS) showing the projection of Q on the ($Q_L - Q_{out}$) plane. Q_{side} is the projection of Q on the axis perpendicular to this plane.

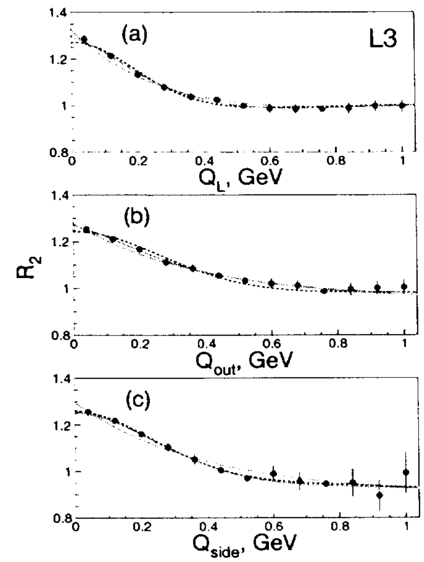

Figure 4: Projections of $R_2(\vec{Q})$ onto the three axes Q_L, Q_{out} and Q_{side}, using the regions up to 240 MeV of the non-projected components. The full lines correspond to projections of the fit with the lowest-order Edgeworth expansion, the dashed lines to those of the Gaussian fit and the dotted lines to the exponential fit.

2.4 L3 analysis using LEP 1 data

L3 has performed a new three dimensional analysis of LEP 1 data [14], using the longitudinal center of mass system (LCMS). This center of mass frame is defined for each pair of particles as the system in which the sum of the momenta of the pair is perpendicular to the thrust axis. With the notations of figure 3, the invariant four-momentum difference can be written as

$$Q^2 = Q_L^2 + Q_{side}^2 + Q_{out}^2(1-\beta^2), \tag{15}$$

where

$$\beta = \frac{p_{out\ 1} + p_{out\ 2}}{E_1 + E_2}, \tag{16}$$

with $p_{out\ i}$ and E_i (i=1,2) the out-component of the momentum and the energy, respectively, of particle i in the LCMS.

The correlation function has been parametrized as a function of $\vec{Q} = (Q_L, Q_{side}, Q_{out})$:

$$R_2(\vec{Q}) = \frac{\rho_2(\vec{Q})}{\rho_0(\vec{Q})}. \tag{17}$$

The reference sample, from which ρ_0 has been determined, has been formed by mixing particles from different events. This mixing procedure introduces some biases which have been estimated by Monte-Carlo using a generator without BEC, and the correlation function has been corrected for. The effect of detector resolution, acceptance, efficiency and particle misidentification have also been corrected.

The following three dimensionnal parametrization has been used [15]:

$$R_2(Q_L, Q_{out}, Q_{side}) = \gamma(1 + \delta Q_L + \epsilon Q_{out} + \zeta Q_{side})$$
$$\times[1 + \lambda \exp(-R_L^2 Q_L^2 - R_{out}^2 Q_{out}^2 - R_{side}^2 Q_{side}^2 + 2\rho_{L,out} R_L R_{out} Q_L Q_{out})], \quad (18)$$

where the factor $(1+\delta Q_L+\epsilon Q_{out}+\zeta Q_{side})$ takes into account possible long-range correlations and γ is a normalization factor. The off-diagonal term $\rho_{L,out} R_L R_{out}$ has been found consistent with zero, and will be fixed to this value in what follows. Other parametrizations have been used: the Gaussian in eq. (18) has been replaced by an Edgeworth expansion, and an exponential fit has also been tried. All the results are compatible with a non-spherically symmetric source. The figure 4 shows the projections of $R_2(\vec{Q})$ onto the three axes Q_L, Q_{out} and Q_{side}, using the regions up to 240 MeV of the non-projected components.
For the Gaussian fit, the longitudinal radius is found to be larger than the transverse radius:

$$R_{side}/R_L = 0.80 \pm 0.02\ (stat)^{+0.03}_{-0.18}\ (syst). \quad (19)$$

This result indicates the existence of an elongated source.

3 Color Reconnection

The model of color rearrangement from Ellis and Geiger [17] has predicted a very large effect, but has been shown not to reproduce the data, either at the Z^0 peak or at higher energies [18].

In the ALEPH analysis, the experimental distributions of $-\ln x_p = -\ln(2p/\sqrt{s})$, where p is the momentum of charged particles, have been compared to Monte-Carlo simulations, with and without Color Reconnection (CR). The W pair events have been generated with the KORALW [19] and EXCALIBUR [20] generators without implementation of CR, and with the EXCALIBUR generator with implementation of CR. In this case, different JETSET models of CR have been used as fragmentation models [21]. These models predict small decrease (~ -0.3) of the charged particle multiplicity of the $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ events compared to twice those of $W^+W^- \rightarrow q_1\bar{q}_2 l\nu_l$ events. Other models, as HERWIG [22,18] or ARIADNE [23], predict similar effects. Figure 5 shows the $-\ln x_p$ distributions for semi-leptonic WW decay (2q) and for fully hadronic WW decay (4q). The ratio of the (4q) distribution to twice the (2q) one is also shown, and compared to different Monte-Carlo predictions, with and without CR. The sensitivity of charged particle multiplicity to CR is rather low, and results are compatible with models both with and without CR.

Table 1 summarizes the measurement of $\Delta < N_{ch} >$ done by the LEP experiments, where $\Delta < N_{ch} > = < N_{ch}^{4q} > -2 < N_{ch}^{2q} >$, with $< N_{ch}^{4q} >$ the mean charged particle multiplicity of fully hadronic events and $< N_{ch}^{2q} >$ those of semi-leptonic events.

	$\sqrt{s}$ (GeV)	$\Delta < N_{ch} >$
ALEPH [18]	183	$+1.31 \pm 0.74 \pm 0.37$ (prel)
L3 [24]	183	$-1.0 \pm 0.8 \pm 0.5$ (prel)
OPAL [25]	183	$+0.7 \pm 0.8 \pm 0.6$
ALEPH [21]	189	$+0.47 \pm 0.44 \pm 0.26$ (prel)

Table 1: Measurement of the difference between the mean charged multiplicity of the $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ events and twice those of $W^+W^- \rightarrow q_1\bar{q}_2 l\nu_l$ events measured by ALPEH, L3 and OPAL experiments. The first error is statistical, the second is systematic.

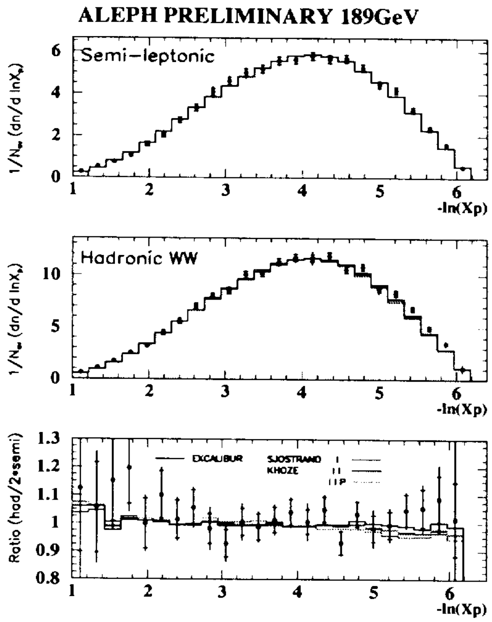

Figure 5: The $-\ln x_p = -\ln(2p/\sqrt{s})$ distributions for the WW semi-leptonic events and WW fully hadronic events for the data and the Monte-Carlo, with and without color reconnection.

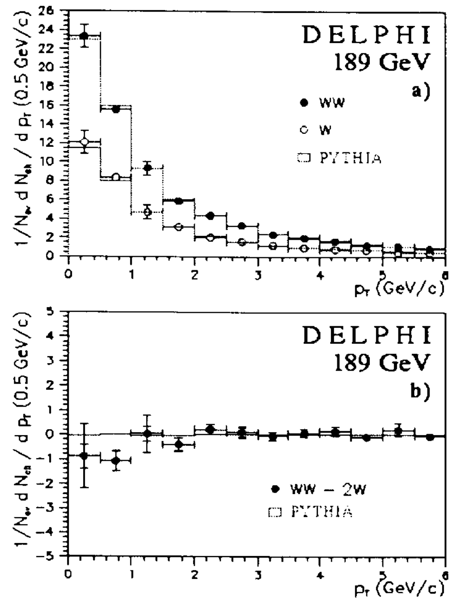

Figure 6: (a): p_T distributions for (4q) events (closed circles) and (2q) events (open circles), compared to simulation without color reconnection, at 189 GeV. The difference between (4q) and twice (2q) is shown in (b).

DELPHI has measured [26] the ratio between the multiplicity in (4q) events and twice the multiplicity in (2q) events. The results are

$$\left(\frac{< N_{ch}^{4q} >}{< N_{ch}^{2q} >}\right)_{189\ GeV} = 0.977 \pm 0.017\ (stat) \pm 0.027\ (syst), \tag{20}$$

$$\left(\frac{< N_{ch}^{4q} >}{< N_{ch}^{2q} >}\right)_{183\ GeV} = 0.941 \pm 0.025\ (stat) \pm 0.023\ (syst). \tag{21}$$

A possible depletion of the multiplicity in the fully hadronic WW events with respect to twice the semi-leptonic events is observed, at the percent level. This depletion is concentrated in the low p_T region, where p_T is the transverse momentum of charged particles with respect to the thrust axis. The p_T distributions are shown in figure 6 for 189 GeV data. However, the significance is less than two standard deviations at 183 GeV and one standard deviation at 189 GeV.

4 Conclusion

BEC have been measured in W pair decays by the LEP collaborations. Opposite conclusions are obtained by ALEPH and DELPHI, using different variables and different methods of analysis: in the (4q), ALEPH favours correlations within the same W only whereas DELPHI favours correlations within the same W and between the W also. The parametrization used by these two collaborations assumed a spherically symmetric source which emits pions. L3 has shown, using the high statistic of LEP 1 data, that the source is elongated and not spherically symmetric. This result is confirmed by a similar DELPHI analysis [16]. Charged particle multiplicities of W

pair events have been measured. No strong evidence of CR is seen. Nevertheless, possible depletion of the multiplicity in the fully hadronic WW events with respect to twice those of the semi-leptonic events is observed by DELPHI.

Acknowledgments

I thank the organizing committee and the european community for their financial support. All the LEP collaborations thank their colleagues from the CERN accelerator divisions for the successful operation of LEP.

References

1. G. Goldhaber et al., *Phys. Rev.* **120**, 300 (1960)
2. ALEPH collaboration, *Z. Phys.* C **54**, 75 (1992)
3. DELPHI collaboration, *Phys. Lett.* B **286**, 201 (1992)
4. OPAL collaboration, *Z. Phys.* C **72**, 389 (1996)
5. DELPHI collaboration, *Phys. Lett.* B **401**, 181 (1997)
6. OPAL collaboration, CERN-EP/98-174
7. T. Sjöstrand and V.A. Khoze, *Z. Phys.* C **62**, 281 (1994)
8. L. Lönnblad and T. Sjöstrand, *Eur. Phys. J.* C **2**, 165 (1998)
9. ALEPH collaboration, *Phys. Lett.* B **313**, 535 (1993)
10. ALEPH collaboration, Contribution to this conference, ALEPH-CONF 99-021
11. DELPHI collaboration, Contribution to this conference, DELPHI 99-22
12. T.Sjöstrand, *Comp. Phys. Com.* **82**, 74 (1994)
13. L3 collaboration, L3-2268, Contribution to HEP conference at Vancouver, 1998
14. L3 collaboration, Contribution to this conference, L3-2375,
15. S.Chapman, P. Scotto and U.Heinz, *Phys. Rev. Lett.* **74**, 4400 (1995)
    S.Chapman, J.R. Nix and U.Heinz, *Phys. Rev.* C **52**, 2694 (1995)
16. O.Smirnova, private communication
    B.Lörstad, O.G. Smirnova, "Transverse Mass Dependence of Bose-Einstein Correlation Radii in e^+e^- Annihilations at LEP Energies", Proc. 7^{th} Int. Workshop on Multiparticle Production "Correlations and Fluctuations", eds. R.C. Hwa *et al.* (World Scientific, Singapore, 1997, p42).
17. J. Ellis and K. Geiger. *Phys. Rev.* D **54**, 1967 (1996), *Phys. Lett.* B **404**, 230 (1997)
18. ALEPH collaboration. Contribution to ICHEP, Vancouver, 1998, ALEPH-CONF 98-036
19. M. Skrzypek, S. Jadach, W. Placzek and Z. Wąs, *Comp. Phys. Com.* **94**, 216 (1996)
20. F.A. Berends, R. Pittau and R. Kleiss, *Comp. Phys. Com.* **85**, 437 (1995)
21. ALEPH collaboration. Contribution to this conference, ALEPH-CONF 99-020
22. G. Marchesini *et al.*, *Comp. Phys. Com.* **67**, 465 (1992)
23. G. Gustafson and J. Häkkinen, *Z. Phys.* C **64**, 659 (1994)
    C. Friberg, G. Gustafson and J. Häkkinen, *Nucl. Phys.* B **490**, 289 (1997)
24. L3 collaboration, L3-2278, Contribution to HEP conference at Vancouver, 1998
25. OPAL collaboration, CERN-EP/98-196
26. DELPHI collaboration. Contribution to this conference, DELPHI 99-21